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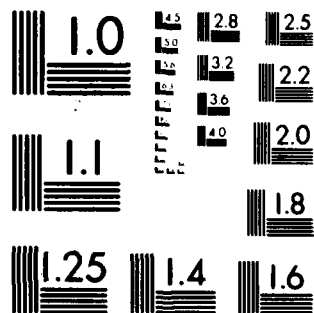
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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Nuclear magnetic resonance	Magnetic interactions
Critical density fluctuations	Superfluid helium 4
Xenon	Vortex motion
Mixed valence	Tkachenko waves
Anderson lattice	Landau critical velocity (over)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A summary is given of research in nuclear magnetic resonance, mixed valence compounds, superfluid helium 4, superfluid helium 3, thermal, magnetic and electrical transport properties of granular aluminum and electron paramagnetic resonance accomplished with the aid of helium gas supplied by this contract.

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Block 19. KEY WORDS (continued)

Superfluid helium 3
Millikelvin temperatures
Coherence length
Helmholtz fourth sound resonator
Anisotropy
Granular metals
Superconductivity
Negative magnetoresistance

Hall coefficient
Localization
Percolation
Electron spin resonance
Crystal field
Covalency
Crystal packing

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Final Letter Report

Contract N00014-76-C-1064

Submitted by: Peter Lindenfeld
Peter Lindenfeld,
Professor of Physics

Under the terms of this contract we received periodic shipments of helium gas for the research needs of this department. The gas was liquified here, and a major fraction of the evaporated gas was recovered for subsequent use.

The staff members whose research required liquid helium were Professors Carr, Croft, Glaberson, Kojima, Lindenfeld, McLean, and Pifer. In the subsequent sections we summarize their recent activities. A list of their publications is appended at the end.

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Nuclear Magnetic Resonance (Carr)

During the period 1 May 1976 through 30 April 1979 work took place in two major areas: (1) NMR Studies of Critical Phenomena and Phase Transitions in 3-Dimensional Liquid-Vapor Systems, and (2) NMR Studies of the Indirect Electron-coupled Nuclear Spin-Spin Interaction and Chemical Shifts in the HD Molecule. Near the end of the above period work was initiated in a third major area, (3) NMR Studies of Phase Transitions in Rare Gas Submonolayers.

The major accomplishment of the above period was published in December of 1977 in an article by C. E. Hayes and H. Y. Carr, "NMR Measurement of the Liquid-Vapor Critical Exponents β and β_1 " [Phys. Rev. Lett. 39, 1558 (1977)]. Before that time there had been a long-standing discrepancy between the experimental values for the critical exponent β which is used to describe the shape of the liquid-vapor coexistence curve and the lattice-gas (Ising model) values calculated using series expansion techniques. More recently the otherwise very successful renormalization group theory was used to calculate β but again with a result somewhat closer but nevertheless in clear disagreement with the commonly accepted experimental value for β .

In 1969 we had introduced a new NMR technique for measuring very accurately the local density in fluid samples such as xenon [Stacey, Pass, and Carr, Phys. Rev. Lett. 23, 1424 (1969)]. From that work it was clear that the liquid-vapor coexistence curve could not be described by a pure power law, as was commonly assumed. Instead correction terms were needed unless one was very near the critical point. Secondly, from the same work it was very clear that one could not get close enough to T_c to measure the asymptotic exponent β without encountering severe problems from gravitationally induced density gradients.

In the above 1977 article a new technique--a quenching technique--was reported which enabled the asymptotic exponent β to be measured effectively in the absence of the density gradients. The result was in close agreement with the existing theoretical values. Moreover the exponent β_1 associated with the first correction term was also measured and found to be in agreement with the renormalization group theory predictions. A copy of the 1977 paper is attached.

During the same period several major accomplishments were achieved in connection with the HD project. They have been reported in detail in the Ph.D. thesis of James R. Beckett (Rutgers, May 1979). They are also being reported in two articles presently in preparation by J. R. Beckett and H. Y. Carr: (a) "Measurement of the NMR Shielding Isotope Shift in D_2 and HD", and (b) "High-Precision Double-Resonance Studies of the Temperature, Density, and Isotope Dependence of the Indirect Electron-Coupled Interaction in HD".

All of the above work was critically dependent on the operation of high-homogeneity, high-stability, and high-field superconducting magnet. The liquid helium for this was provided for by the grant noted in the title of this report. The magnet has been operating in the persistent mode continuously for the past four years.

Mixed Valence Compounds (Croft)

Cerium in elemental and compound form can occur in either a Ce^{3+} valence state with a local magnetic moment or in a Ce^{4+} valence state with no local magnetic moment. We are studying both the strongly lattice-coupled valence instability and the magnetic-nonmagnetic instability which occurs in Ce compounds which are chemically driven from the Ce^{3+} state toward the Ce^{4+} state. Specifically we have studied the lattice and transport and magnetic properties of the $Ce_{1-x}R_xAl_2$ systems with $R = Th^{4+}, Eu^{2+}, Y^{3+}$ and Sc^{3+} . The systematic increase of the spin fluctuation energy scale and decrease of interatomic magnetic interaction energy scale precursive to the valence instability have been observed. Since the temperature range of these studies has been $1.5\text{ K} < T < 300\text{ K}$ we have relied heavily on the Rutgers helium recycling facility. Some of the results of these alloy studies on $CeAl_2$ are 1) the rate of depression of the magnetic ordering temperature with concentration x increases on going from Y to Sc to Eu substitution. 2) the substitution increases the ordering temperature. 3) in the Sc substituted system the

spin fluctuation energy scale (the energy scale for loss of local moment magnetism) increases exponentially from 5 K at $X=0$ to about 100 K at $X = .7$.

Superfluid Helium 4 (Glaberson)

We have continued our research on the properties of rotating superfluid helium. We have completed a series of experiments on temperature and potential gradients which are associated with the motion of vortex lines. We have made extensive observations of wave propagation along single vortex lines and of collective waves in vortex arrays. The effects of surface roughness on the pinning of vortices to surfaces has been investigated. Using fourth sound techniques, we have measured the temperature dependence of the Landau critical velocity.

Superfluid Helium 3 (Kojima)

We have carried out experiments to probe the heat transport across the interface between liquid/solid ^3He and magnetic materials at ultra low temperatures. Our experiments were designed to test interesting theoretical predictions based on an unusual magnetic interaction between ^3He nuclei and the electrons in the magnetic material. Our preliminary results indicate that such magnetic interaction effects are small and that the physical size of the magnetic material plays an important role in the heat transport. We have initiated an investigation of the anisotropic properties of superfluid ^3He using acoustic techniques. We have developed annular and Helmholtz resonators which can be used to measure the superfluid density and the viscosity of the liquid ^3He below 10 mK. We have investigated the effects of the variation of temperature and pressure as well as the resonator parameters on the resonance frequency and the resonance quality. We have recently initiated studies on the size effects on superfluid ^3He confined in restricted geometry using fourth sound techniques and have found for the coherence length of superfluid ^3He to be approximately $\xi_0 \approx 200 \text{ \AA}$.

Thermal Measurements of Granular Aluminum (Lindenfeld)

Thermal conductivity measurements in low resistivity material below the superconducting transition temperature have shown that the electronic contribution is like that of impurity-dominated superconductors and is well described by the Bardeen, Rickayzen, and Tewordt theory. In the normal state it follows the Wiedemann-Franz law. In high resistivity specimens the electronic contribution is dominated by the phonon conductivity. A plateau has been found in the curve of thermal conductivity as a function of temperature corresponding to dominant phonon wavelength coinciding with grain diameter. A new and as yet unexplained effect was discovered in magnetic fields of about 800 G. With the field perpendicular to the sample, a sharp minimum was found in the thermal conductivity.

The heat capacity measurements referred to in earlier reports have now been published. These have stimulated percolation theory calculations which have been remarkably successful in accounting for the detailed changes in the dependence of heat capacity on temperature as one increases the electrical resistivity of the specimens as well as for the difference between the heat capacity and electrical resistivity transition temperatures.

Magnetic Susceptibility of Superconducting Granular Aluminum (McLean)

Results well below the superconducting transition temperature give the zero temperature penetration depth. In low resistivity samples, this is found to vary with resistivity in the way expected for impure metals. At resistivities near to $8000 \mu\Omega\text{cm}$ the penetration depth diverges, owing to the decoupling of the grains which are too small to be detectable when they are independent of each other. It is just about this resistivity that the discontinuity in heat capacity at the superconducting transition temperature disappears for the same reason. In both cases the thermal fluctuations are expected to be so large even at absolute zero that no evidence of superconductivity can be detected.

The behavior at the superconducting transition temperature also gives information about the coupling of the grains. Even at this temperature the coupling remains appreciable, except in samples of resistivity close to $8000 \mu \Omega \text{ cm}$.

Electrical Resistivity of Granular Aluminum (Lindenfeld & McLean)

In the course of studying the contributions to the conductivity of the superconducting fluctuations above the transition temperature we became involved with an area that is currently of great interest--the localization of electron states in inhomogeneous metals. A number of the results have been published or are in press but this continues to be our major interest at present. High resistivity granular aluminum shows evidence of localization. We are currently carefully establishing the law of dependence of normal state resistivity on temperature and correlating this with the occurrence of superconductivity. We have now completed the construction of a helium three system that has enabled us so far to make measurements to 0.31 K.

In our earlier work on granular aluminum we found a magnetoresistance that was unexpectedly large and negative. We have been able to rule out some existing theories as explanations of the effect. We have begun measurements on gold grains in silicon dioxide and plan investigating other granular metal systems in order to check further explanations.

We are beginning to get results in our Hall effect measurements on granular aluminum. In three different samples the Hall coefficient increases with resistivity, as expected from recent percolation theory for samples above the percolation threshold.

Electron Paramagnetic Resonance (Pifer)

We are studying the low temperature EPR of d^1 electrons on tetrahedral MO_4 complexes (where $M = V^{4+}, Cr^{5+}, Mn^{6+}, Nb^{4+}$ or Mo^{5+}) imbedded in a variety of insulating compounds. The EPR allows an accurate determination of the distortion of a given MO_4 complex from tetrahedral symmetry due to crystal packing effects and yields crystal field and covalency parameters. Work is also in progress on developing a diamond anvil system to study the EPR of various intermetallic compounds at pressures up to 100 kbar and at liquid helium temperatures.

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